Summary of RADCOR 98

R. D. Peccei

Department of Physics and Astronomy, UCLA, Los Angeles, CA 90095-1547

Abstract

This summary is organized in four parts. In the first part results in the electroweak theory are discussed, including precision tests of the Standard Model. The second part deals with recent results in QCD, focusing on areas where meaningful comparisons between theory and experiment are possible. The third part summarizes some of the salient technical progress in studying two-loop radiative effects in a variety of contexts, as well as progress made in calculating radiative corrections in the LEP 200 region. Finally, in the fourth part, a discussion of the effects of radiative corrections, both as a result of new physics and in new energy regimes, is presented focusing on their future experimental implications.

1 Introduction

This Fourth Symposium on Radiative Corrections, following earlier meetings at Brighton, Knoxville and Krakow, amply demonstrated the vitality and relevance of this topic. Radiative corrections are the bridge that joins quantum field theory to phenomenology. In the electroweak theory they help validate the Standard Model and circumscribe possible new phenomena. At Barcelona, there were strong hints that the "old" success of radiative corrections in predicting the top mass may well be followed by a new success, that of predicting a light Higgs. In more established theories, like QED and QCD, radiative corrections help to organize the way one thinks about phenomena which by themselves are non-perturbative in nature—phenomena like confinement, hadronization and bound state decays.

There were far too many talks in RADCOR 98 to be able to summarize them in detail, even if I could! Hence, I opted instead to make comments on some of the results and give my overall impressions in different areas. Roughly speaking, these comments can be organized under four rubrics: Results in the Electroweak Theory; QCD Results; Technical Progress; and Future Tests.

The above divisions, however, are not sharp. For instance, QCD radiative corrections are clearly important for precision electroweak tests. Also, much of the technical progress involves re-expanding or resumming certain QCD and/or electroweak results. Finally, future tests often involve radiative effects in new regimes of the Standard Model itself. In a nutshell, one could summarize the conclusions for these four topics very simply: all is well in the electroweak sector; QCD works; impressive technical advances continue to be made; and future experiments will surely open up new physics windows. However, let me be a bit more specific!

2 Results in the Electroweak Theory

Substantial new data has sharpened our understanding of the electroweak theory and its parameters. At RADCOR 98 the experimental situation was ably summarized in three separate talks. F. Teubert[1] reviewed precision tests of the standard model at the Z resonance; E. Lançon[2] talked about LEP 200 results, particularly those concerning W physics; and M. Tuts[3] discussed results on top and W's coming from the Tevatron Collider. Wolfgang Hollik,[4] in his own overview talk, discussed how this data compared in detail with the standard electroweak theory. He concluded that there was total consistency between theory and experiment at the level of accuracy of a tenth of a percent—a remarkable feat! Let me briefly outline the main results presented.

2.1 Top

The CDF and DO combined results for the top mass, presented at this conference by Tuts,[3] now make top the quark whose mass is best known. The combined result

$$m_t = (173.8 \pm 3.2 \pm 3.9) \text{ GeV} = (173.8 \pm 5.0) \text{ GeV} \qquad (1)$$

has a relative error $\delta m_t/m_t$ of less than 3%—an extraordinary result. In addition, CDF and DO have a quite accurate determination of the top pair production cross-section[3]

$$\sigma_{t\bar{t}} = \left\{ \begin{array}{ll} (5.9 \pm 1.7) \text{ pb} & \text{DO} \\ \left(7.6^{+1.8}_{-1.5}\right) \text{ pb} & \text{CDF} \end{array} \right. \qquad (2)$$

in good agreement with the theoretical QCD predictions, which range from 4.7 to 6.2 pb.

2.2 $W^{\pm}$

Precise values for M_W are inferred from studies of the process $e^+e^- \to W^+W^-$ at LEP2 [2] and from W production at the Tevatron.[3] Combining the threshold analysis of the W mass at $\sqrt{s} = 161$ GeV with the value of M_W obtained by direct reconstruction at both $\sqrt{s} = 172$ GeV and $\sqrt{s} = 183$ GeV, the averaged results from the four LEP collaborations determine the W mass to 90 MeV [2]

$$\begin{aligned} M_W &= (80.37 \pm 0.07 \pm 0.04 \pm 0.02) \text{ GeV} & (3) \\ &= (80.37 \pm 0.09) \text{ GeV} . & (4) \end{aligned}$$

In the above, the dominant error (70 MeV) is statistical, with about 40 MeV coming from not being able to disentangle final state interactions between the two produced W's and 20 MeV arising from uncertainties in the beam energy.

A similar error is obtained by combining the values for M_W obtained by the CDF and DO collaborations (as well as from the old UA2 data),[3] giving a "collider value" for M_W of

$$M_W = (80.40 \pm 0.09) \text{ GeV} . \tag{5}$$

The world average for M_W, determined from the above two direct measurements, has an error of 60 MeV [5]

$$M_W|_{\text{direct}} = (80.39 \pm 0.06) \text{ GeV} , \tag{6}$$

so that now we know the W mass to better than 1 part per mil. This value is in good agreement with the new NUTEV result from deep inelastic neutrino scattering [6] for the weak mixing angle

$$(\sin^2 \theta_W)_S = 1 - M_W^2/M_Z^2 = 0.2253 \pm 0.0019 \pm 0.0010 , \tag{7}$$

which determines the W-mass to an accuracy of 110 MeV

$$M_W = (80.26 \pm 0.11) \text{ GeV} . \tag{8}$$

Eq. (6) also agrees very well with the very precise indirect W mass determination obtained from a global fit of all other high precision eletroweak data, which gives [1]

$$M_W|_{\text{indirect}} = (80.365 \pm 0.030) \text{ GeV} . \tag{9}$$

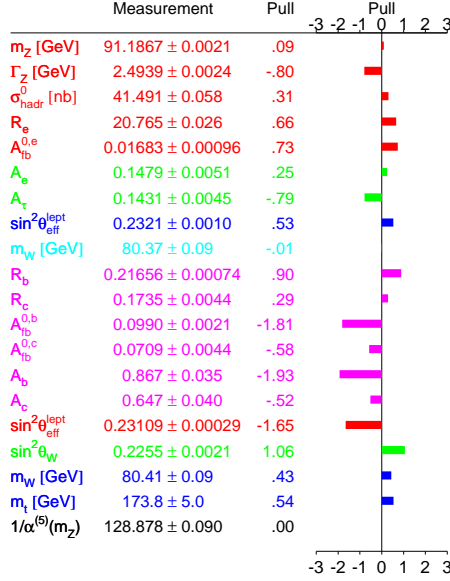I comment below on this latter fit and its implications.

	Measurement	Pull	Pull -3 -2 -1 0 1 2 3
m_Z [GeV]	91.1867 ± 0.0021	.09	
Γ_Z [GeV]	2.4939 ± 0.0024	-.80	
σ^0_{hadr} [nb]	41.491 ± 0.058	.31	
R_e	20.765 ± 0.026	.66	
$A^{0,e}_{fb}$	0.01683 ± 0.00096	.73	
A_e	0.1479 ± 0.0051	.25	
A_τ	0.1431 ± 0.0045	-.79	
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.53	
m_W [GeV]	80.37 ± 0.09	-.01	
R_b	0.21656 ± 0.00074	.90	
R_c	0.1735 ± 0.0044	.29	
$A^{0,b}_{fb}$	0.0990 ± 0.0021	-1.81	
$A^{0,c}_{fb}$	0.0709 ± 0.0044	-.58	
A_b	0.867 ± 0.035	-1.93	
A_c	0.647 ± 0.040	-.52	
$\sin^2\theta^{lept}_{eff}$	0.23109 ± 0.00029	-1.65	
$\sin^2\theta_W$	0.2255 ± 0.0021	1.06	
m_W [GeV]	80.41 ± 0.09	.43	
m_t [GeV]	173.8 ± 5.0	.54	
$1/\alpha^{(5)}(m_Z)$	128.878 ± 0.090	.00	

-3 -2 -1 0 1 2 3

Figure 1: Standard Model fit.

2.3 Precision Tests at the Z-Resonance.

Precision measurements at the Z resonance,[1] plus a knowledge of m_t and M_W, overconstrain the Standard Model. Thus, as Hollik [4] emphasized, present-day data provides rather significant tests of the electroweak theory. Fits of all electroweak data to the Standard Model are in terrific agreement with expectations, with very few quantities in the fit being over 2σ away from the fit value. This is nicely seen in Fig. 1 which summarizes the Standard Model analysis presented by Grünewald [7] at the International Conference on High Energy Physics in Vancouver this summer. Not only is the data consistent with the Standard Model, but as Teubert [1] emphasized it is also internally consistent. This was most clearly seen in the comparison of different determinations of $\sin^2\theta^{\rm eff}_W$ at both LEP and SLD which are also at most 2σ away from the average value

$$\sin^2\theta^{\rm eff}_W = 0.23155 \pm 0.00018 . \tag{10}$$

In the Standard Model, given G_F, α, M_Z and m_t, the only free parameter remaining is the Higgs mass M_H. Unfortunately, even the present high
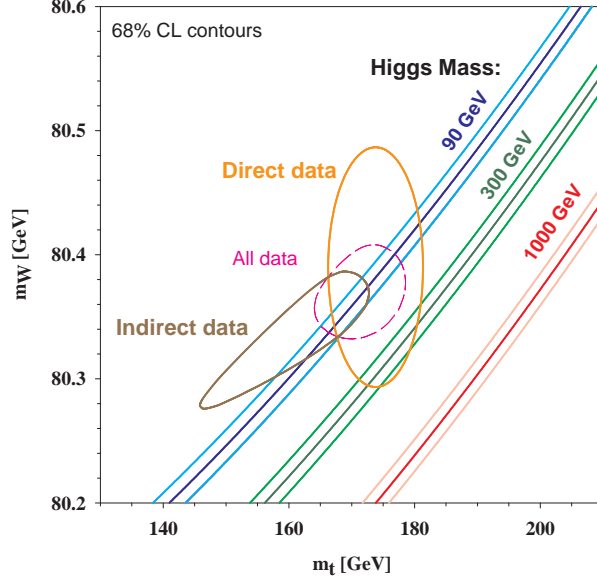
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Figure 2: Allowed contours in the M_W-m_t plane.

precision data does not give a strong constraint on M_H, since the effects of the Higgs mass are only proportional to $\alpha \ln M_H$. Nevertheless, the 68% CL contours in the $M_W - m_t$ plane shown in Fig. 2, determined both through Standard Model fits and by the direct measurements of m_t and M_W, favor a low value for the Higgs mass

$$M_H|_{\text{rad. corr.}} = \left(84^{+91}_{-51}\right) \text{ GeV} , \qquad (11)$$

leading to a one-sided 95% CL bound for M_H of $M_H < 262$ GeV.[1]

Errors in G_F and M_Z are insignificant for precision tests, while errors in m_t and $\alpha(M_Z^2)$, as well as the M_H dependence, affect different quantities differently. For instance,[1] $\sin^2 \theta_W^{\text{eff}}$ is most strongly dependent on the error in $\alpha(M_Z^2)$ and on the Higgs mass dependence, while [8] R_b is most sensitive to δm_t. Because the radiative effects have a quadratic sensitivity on m_t, precision electroweak data alone provide a strong "prediction" for the top mass. Indeed, if m_t is taken as unknown in the fit, then one predicts [1]

$$m_t|_{\text{rad. corr.}} = \left(161.1^{+8.2}_{-7.1}\right) \text{ GeV} . \qquad (12)$$

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2.4 Higgs

Fig. 3 shows the present situation regarding the Higgs mass. The vertical line displays the direct mass limit on the Higgs obtained at LEP 200[2] from Higgs searches in the process $e^+e^- \to ZH$. Using the $\sqrt{s} = 183$ GeV data for all four LEP experiments[9] one finds:

$$M_H > 89.8 \text{ GeV} \qquad (95\% C.L.) \tag{13}$$

I will discuss a little later on the error band on the Higgs mass in Fig. 3. However, here I want to discuss briefly the prospect of "improving" the Higgs upper bound by reducing the error in $\alpha^{-1}(M_Z^2)$. As can be seen in Fig. 3, the changes effected by using instead of the "standard value" $\alpha^{-1}(M_Z^2) = 128.878 \pm 0.090$, the "improved value" $\alpha^{-1}(M_Z^2) = 128.905 \pm 0.036$ are quite significant. As Jegerlehner[10] pointed out at RADCOR 98, the improvement in the error is essentially due to the perturbative QCD improved value for $\delta\Delta\alpha^5$, which is reduced by about a factor of 5. Jegerlehner thought this reduction to be highly optimistic, not because the theoretical method is unreliable but because it is difficult to identify the experimental contributions to this accuracy. In addition, as Gambino[8] emphasized, real improvements in the Higgs upper bound need a parallel reduction in δm_t and δM_W to about 2 GeV and 30 MeV, respectively.

2.5 Theoretical Remarks.

There are two theoretical remarks on precision tests, made at RADCOR 98, which are worth repeating here. It is often said that the precision tests of the electroweak theory essentially are only sensitive to the running of α from $\alpha(0)$ to $\alpha(M_Z^2)$. However, as Hollik explained,[4] this is not really the case. For instance, one now has a value for the ρ parameter which is different from unity at 3σ:

$$\rho = 1.0042 \pm 0.0012 \ . \tag{14}$$

Also, when one examines the radiative shift Δr, it is not true that the result is dominated by the running of α. Rather, schematically,[4] one has

$$\Delta r = \Delta\alpha - (\cos^2\theta_W / \sin^2\theta_W)\Delta\rho + \Delta r_{\text{rest}} \ . \tag{15}$$

While the first term contributes at the 6% level, the others contributes at the 4% level and 1% level, respectively. So, really, $\Delta\alpha$ does not dominate.
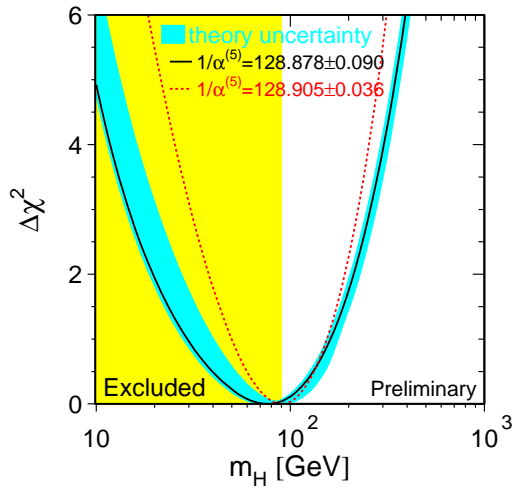
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Figure 3: Allowed region for M_H from radiative corrections.

A second important point to make[4,11] is that an excellent Standard Model fit to the data **does not** exclude an equally good MSSM fit. Rather, the good agreement of the data with the Standard Model serves to provide useful constraints for sparticles and SUSY parameters, but does not exclude having supersymmetry at or near, the weak scale. For example, de Boer,[11] showed a very nice fit of all the precision data (of similar quality to that of Fig. 1) in the MSSM, provided one took $|\mu| > m_{1/2}$; $m_{\tilde{q}} \sim 300$ GeV; $m_h < 105$ GeV and $\tan\beta = 1.65 \pm 0.3$. While specific results are model dependent, two points appear common in these MSSM fits. First, as is well known and as I will discuss more later on, in supersymmetric theories there is always a light Higgs. Second, however, the light Higgs in the MSSM gives rise to a band which is systematically above the Standard Model light Higgs band (see Fig. 2) in the $M_W - m_t$ plane. From this point of view, decreasing the errors in the top and W masses would be very important, as it could discriminate between these two alternatives.[4]

3 QCD Results

In his plenary talk on QCD at the International Conference on High Energy Physics in Vancouver this summer, Yuri Dokshitzer[12] made the remark that

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since QCD is a mature theory "the issue is not to check QCD, but to see how it works". At RADCOR 98 many beautiful examples were presented of how indeed QCD works. I will discuss some of them here.

3.1 $b \to s\gamma$

Although the process $b \to s\gamma$ is an electroweak process, it is particularly sensitive to QCD corrections since these corrections change the nature of the GIM cancellation from quadratic $[m_t^2 - m_c^2]$ to logarithmic $[\ln m_t^2/m_c^2]$. Gambino[8] discussed the NLO analysis of this process in Barcelona. The result obtained for the branching ratio for this process in NLO

$$\text{BR}(B \to X_s\gamma)|_{\text{NLO}} = (3.29 \pm 0.30) \times 10^{-4} \tag{16}$$

is considerably larger than the lowest order result:

$$\text{BR}(B \to X_s\gamma)|_{\text{LO}} = (2.46 \pm 0.72) \times 10^{-4} \ . \tag{17}$$

More importantly, this result is in excellent agreement with the new CLEO (and ALEPH) branching ratio discussed at the meeting by G. Eigen[13]

$$\text{BR}(B \to X_s\gamma)|_{\text{CLEO}} = (3.15 \pm 0.35 \pm 0.32 \pm 0.26) \times 10^{-4} \ , \tag{18}$$

where the last error above is an estimate of the uncertainty caused by the models used to extract this branching ratio from the data.

3.2 Deep Inelastic Scattering.

At RADCOR 98 there were two presentations[14,15] of the most recent results from HERA. These talks demonstrated in a beautiful way QCD at work in deep inelastic scattering. This was apparent in the wonderful and very precise data on $F_2(x, Q^2)$, where one could see with the naked eye very little Q^2-dependence for large x and considerable dependence at low x–just what QCD ordered! As Forte[16] emphasized in his talk, the scaling violations at small x can be used to extract simultaneously the gluon distribution and $\alpha_s(Q^2)$ since, in this region, approximately,

$$\frac{dF_2}{d\ln Q^2} \sim \alpha_s(Q^2) x g(x, Q^2) \ . \tag{19}$$

This analysis is apparently under way, but has not been done yet. What has been done, however, is to get a first idea of the gluon distribution function from

the behavior of the di-jet cross sections at HERA.[15] This distribution function, as expected, rises sharply as x becomes smaller. However, the errors are still too large to effectively discriminate among different pdf parametrizations.

Hernandez[14] discussing the sharp rise at low x, for fixed Q^2, of $F_2(x, Q^2)$, suggested that possibly this rise was not accountable by the usual DGLAP evolution equations. Forte,[16] however, was not convinced. Indeed, he discussed the analysis tht he and Ball[17] did of earlier HERA data on $F_2(x; Q^2)$ at small x (and for a range of Q^2), where using DGLAP they actually were able to extract already quite a good value for $\alpha_s(M_Z^2)$:

$$\alpha_s(M_z^2)|_{\mathrm{BF}} = 0.120 \pm 0.005 \pm 0.009 . \tag{20}$$

Clearly, as discussed above, one awaits a full analysis of the evolution of $F_2(x, Q^2)$ at small x by the HERA experimental collaborations to get more accurate results on both α_s and the gluon distribution function.

3.3   Jet Physics.

Hadronic jets are ubiquitous features of hard scattering processes and are well described by QCD. However, for more detailed observables, comparison of data with QCD is more subtle. A nice example of the subtleties involved was discussed by Bethke[18] at RADCOR 98, involving the ratio of multiplicities of gluon jets relative to quark jets. In QCD, as is well known, this ratio at asymptotic energies is simply given by a color factor, with $\langle n \rangle_g / \langle n \rangle_q = 9/4$. One can nicely study gluon jets at LEP by focusing on $Z \to b\bar{b}g$, since one can identify the b-jets. If one does this with no selection in the data, one finds a, dissapointingly low, result:

$$\left. \frac{\langle n \rangle_g}{\langle n \rangle_q} \right|_{\mathrm{no-selection}} = 1.27 \pm 0.07 . \tag{21}$$

On the other hand, if one selects events in which the $b\bar{b}$ jets are almost collinear and back to back to the gluon jets—thus producing gluon jets of rather high energy ($\langle E \rangle_g = 42$ GeV)—one obtains a much higher number

$$\left. \frac{\langle n \rangle_g}{\langle n \rangle_q} \right|_{\mathrm{selected}} = 1.87 \pm 0.05 \pm 0.12 . \tag{22}$$

The conclusion to be drawn is that, even for these selected events, the energies involved are not yet sufficient to expect the asymptotic QCD prediction to hold.

Nevertheless, with these cuts there is a marked shift of the results towards the QCD expectations.

Bethke [18] also showed that NLO QCD (with some resummation) describes well three- and four-jet distributions at LEP 100, giving tight errors on $\alpha_s(M_Z^2)$ and a mild scale dependence. One can also look at event shape variables obtaining fits where power corrections are correlated, as one would expect from renormalons.[19] For instance, one finds

$$\frac{1}{2}\langle 1 - T \rangle = \frac{1}{3\pi}\langle C \rangle \ . \tag{23}$$

Fits with optimized scales give even smaller errors in α_s for shape variables,[18] but here there is some controversy. For example, DELPHI has done an analysis of 18 shape variables and extracted α_s by a simultaneous fit in which also the scale μ^2 was optimized for each variable.[20] The resulting value of α_s has a very small error

$$\alpha_s(M_Z^2) = 0.1164 \pm 0.0025, \tag{24}$$

but there is considerable variation in the scale parameter, ranging from $\mu^2/M_Z^2 = 0.0033$ to $\mu^2/M_Z^2 = 6.33$. This seems an enormous range to me! For this reason, it seems much more sensible instead, as advocated emphatically by Brodsky [21] at this meeting, to use a fixed but **physical** scale to do the analysis of jet and shape variables. Brodsky rather naturally favors the BLM scale [22] in which different processes are related through appropriate rescalings. Thus α_s for a given process is related to α_s in another process through a rescaling, such that in the resulting power series expansion the coefficients are the conformal coefficients:

$$\alpha_s(Q_A^2) = \alpha_s(Q_B^2) \left[1 + r_1^{B/A} \frac{\alpha_s}{\pi} + ... \right], \tag{25}$$

with

$$Q_A = \xi Q_B \ . \tag{26}$$

With this rescaling, as Brodsky emphasized,[21] all the IR renormalons are absorbed. Obviously, it seems important to check whether this approach really works in detail experimentally. However, to effect this in practice probably needs a stronger push by the theorists than heretofore.

Another area where stronger experimentalist-theorist interactions would be of benefit was pointed out by Zoltan Kunszt [23] in Barcelona. Kunszt presented a review of the recent very impressive multi-leg NLO results obtained analytically with new techniques (helicity methods, collinear limits,

SUSY Ward identities, etc.) by Bern, Dixon and Kosower and their collaborators.[24] During the discussion of these achievements, he bemoaned the fact that many of these results were not yet incorporated in the experimental codes used for data analysis. In this respect, similar comments may well apply in the future for the heavy quark NLO results obtainable by the new method David Soper[25] discussed at RADCOR 98. The idea behind this method is to perform the diagramatic calculations involved by integrating over the energies first, deforming the relevant contours as necessary. In this way one is left with momentum integrals of sums over cuts of **IR insensitive** functions, allowing better numerical handling of mass effects. Although it remains to be seen whether this method will prove effective, clearly if it does it also will need to be incorporated into the experimental codes.

Let me close this section by making one more comment along this vein, but now putting the onus on the theorists rather than on the experimentalists! Bethke,[18] in his talk at RADCOR 98 also briefly reviewed the status of $\alpha_s(M_Z^2)$, quoting a value for the world average of

$$\alpha_s(M_Z^2)|_{\text{world ave}} = 0.1190 \pm 0.006 . \tag{27}$$

In the discussion that followed his talk, it was the view of many theorists that the error on α_s quoted seemed too large, since the most reliable analyses of α_s theoretically in the compilation of Bethke had all a smaller uncertainty than the final error quoted. Bethke's response was that, as an experimentalist, he did not feel he could, without reason, remove some of the less accurate α_s determinations from his compilation, thus perhaps contributing to inflating the error. I agree with him completely. If theorists feel that an error in α_s of $\delta\alpha_s = 0.002$ is possible, then they should volunteer to vet what should enter into the average and be prepared to weed out themselves dubious experimental determinations of α_s. In doing so, they would be doing the field a great service!

4   Technical Progress

Perhaps what impressed me the most at RADCOR 98, as a non-expert, was the amazing technical wizardy at work. Some of this technical firepower was directed at extracting information on the heavy quark mass dependence of a variety of two-loop calculations.

Expansion techniques of different sorts, to handle these m_Q effects, were discussed in a number of talks.[26,28,29,30] The general idea is to reduce the calculations, through the use of recursion relations, to sums of a few Master integrals M_i:

$$A = \sum_i c_i M_i \ . \tag{28}$$

One then evaluates the M_i's in various tractable regions [e.g. $q^2 \gg m_Q^2$; $q^2 \ll m_Q^2$; threshold] as Taylor series expansions. After a conformal map from q^2 to $\omega = \left(1 - \sqrt{1 - q^2/4m_Q^2}\right) / \left(1 + \sqrt{1 - q^2/4m_Q^2}\right)$ one tries to reconstruct the function from the Taylor coefficients, using Padé expansions to improve the accuracy. This procedure works amazingly well, as Kühn[28] demonstrated by showing that one can recover the Coulomb $1/v$ singularities from information coming from the $q^2 \gg m_Q^2$ and $q^2 \ll m_Q^2$ regions.

These techniques are now largely automatized through the development of dedicated computer programs.[29] As a result, one has been able to address a number of issues of interest, and some of these results were discussed in Barcelona. Specifically, Kühn[28] talked about the calculation of R_c and R_b to $O(\alpha_s^2)$ and how these calculations permit the reduction of the theoretical error in $\delta\Delta\alpha^5$ to $\delta\Delta\alpha^5 = 0.00017$. Steinhauser[29] discussed the $O(\alpha_s^2)$ corrections to $H \to t\bar{t}$ and the $O(\alpha\alpha_s)$ corrections to $Z \to b\bar{b}$ (a topic which was also discussed by Fleischer.[26]) Finally, Czarnecki[27] discussed the $O(\alpha_s^2)$ correction to semileptonic processes, an example of which is the process $t \to bW$ where his result is

$$\Gamma(t \to bW) = \Gamma_0[1 - 0.8\alpha_s(m_t) - 1.7\alpha_s^2(m_t)] \ . \tag{29}$$

One of the most interesting by-products of these technical developments is their applicatiion to bound state problems. Here one is interested in examining what happens near threshold and one must develop a set of consistent approximations which identify and include all the dominant physical processes. For the $b\bar{b}$ vacuum polarization graph at 2-loops, Beneke[30] integrated sequentially out different scales in the loops, characterized by the typical size of the loop momenta ℓ_i and energies ℓ_o. Integrating out the hard scales $\ell_o \sim \ell_i \sim m_b$ replaces the QCD Lagrangian by an effective non-relativistic Lagrangian. Integrating out next the soft scales $\ell_o \sim \ell_i \sim m_b v$ modifies this Lagrangian further, producing a non-local potential. Finally, integrating out the scales $\ell_o \sim m_b v^2$, $\ell_i \sim m_b v$ sums up all the $1/v$ Coulomb terms, leaving just ultrasoft terms.

Beneke matched the threshold results he obtained in this way with those deduced by integrating directly over the Υ-resonances, extracting from this procedure a (preliminary) estimate of $m_b(m_b)$. His result [30]

$$m_b(m_b) = (4.37 \pm 0.08) \text{ GeV} , \tag{30}$$

if confirmed, provides an extremely accurate determination for the b-quark mass. Certainly this result is very much more accurate than the value for m_b obtained from studying the process $Z \to bb(g)$. As Rodrigo [31] discussed in Barcelona, using a jet algorithm and a NLO QCD calculation of $Z \to bbg$, the DELPHI Collaboration obtains

$$m_b(M_Z) = (2.65 \pm 0.25 \pm 0.34 \pm 0.27) \text{ GeV} , \tag{31}$$

where the last error is an estimate of the theory uncertainty.

A. Czarnecki [27] applied similar threshold expansion techniques to obtain analytically the $O(m\alpha^6)$ contribution to positronium hyperfine splitting. This is a very hard calculation and a real *tour de force*, where the use of dimensional regularization to handle divergent terms (also used by Beneke) was crucial to obtain the final result. These $O(m\alpha^6)$ terms had been calculated before, but the numerical results obtained, by three different groups, disagreed with each other. The result of Czarnecki's calculation of 11.8 MHz agrees with one of these numerical results. However, the final result obtained for the para-ortho splitting, including this correction, $\Delta E_{\mathrm{p-o}} = 203392$ (1) MHz does not quite coincide with the experimental result obtained some time ago by Vernon Hughes and collaborators: [32] $\Delta E_{\mathrm{p-o}}|_{\exp} = 203389.10$ (0.74) MHz. Thus the hyperfine splitting of positronium has still some remaining issues to be resolved.

In Barcelona, a further impressive analytic calculation was presented—the $O(\alpha^2)$ corrections to μ-decay, discussed by R. G. Stuart. [33] Stuart's work uses different techniques than the ones just described, but is no less remarkable. Writing the μ-decay lifetime as

$$\tau^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3}[1 + \Delta q] , \tag{32}$$

what Stuart discussed is the $O(\alpha^2)$ correction to Δq. Given that the $O(\alpha)$ correction to Δq—the famous Kinoshita, Sirlin [34] and Berman [35] calculation— was computed almost 40 years ago, it is particularly nice to finally have an analytic $O(\alpha^2)$ result: [33]

$$[\Delta q]_2 = \left(\frac{\alpha}{\pi}\right)^2 [6.701 \pm 0.002] , \tag{33}$$

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where the error comes from uncertainties in the hadronic contribution. This calculation removes altogether any theoretical uncertainty in the Fermi constant, so that the new value for G_F has an error which comes entirely from the error on the μ-lifetime itself. Hence, now

$$G_F = (1.16639 \pm 0.00001) \times 10^{-5} \text{ Gev}^{-2} \ . \tag{34}$$

4.2 Electroweak Results

There was also considerable technical progress reported in Barcelona in the electroweak sector. Roughly speaking, this took place in three different areas and, to my mind, in each area it involved efforts of heroic proportions. The first of these efforts was concerned with the full calculation of W^+W^- radiative corrections, taking into account that the W's indeed decay into $f\bar{f}$. Going beyond the on-shell approximation involves a multitude of problems, as was made explicit in the talks of Dittmaier[36] and Behrends.[37] One of these problems is how to preserve gauge invariance in the calculation, since using simply a finite width for the W's does not guarantee this. What can be done, however, is to use a complex mass everywhere (including in the definition of $\cos^2\theta_W$!), which then allows one to respect the Ward identities throughout.[36] The treatment of soft photons is also particularly tricky, as was evident in Behrends' talk.[37] Fortunately, the principal radiation occurs off the W's themselves, and not the final state fermions. Thus the final results are close to those in which the W's are taken to be on shell, and one can match-on to existing calculations rather well.

A second technical thrust in the electroweak sector, which elicited considerable discussions at Barcelona, was the construction of improved codes for LEP 200. M. Skrzypek[38] discussed a new YFS Monte Carlo for WW and ZZ production. This Monte Carlo program is an extension of KORAL W, including $O(\alpha)$ electroweak corrections in the WW and ZZ region, and hopes to eventually achieve a 0.5% precision. W. Placzek[39] talked about the work presently going on to extend the YFS Bhabha Monte Carlo program to larger angles, again for LEP 200. The goal here is to achieve throughout a precision $\delta\sigma/\sigma \le 0.25\%$. T. Riemann[40] discussed improvements in the Z Fitter $e^+e^- \to f\bar{f}(\gamma)$ code to make it effective in the LEP 200 region. In particular, one must include appropriate radiator cuts so as to get rid of Z radiative returns. Finally, G. Passarino[41] discussed some of the challenges one encounters in trying to implement a program for inclusive $q\bar{q}$ production $[e^+e^- \to q\bar{q}X]$. Such a program must include, for example, also $q\bar{q}$'s coming from W-decay

[i.e. $e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}X$]. In trying to consider the totality of effects associated with inclusive $q\bar{q}$ production, the hardest problems are those connected with soft radiation. The goal, as Passarino explained,[41] is to be able to separate effectively the result into a sum of singular and non-singular terms, with negligible interference. However, this can be very challenging in practice!

A third important topic of activity centered around how to reduce the uncertainty on the Higgs mass prediction from electroweak measurements. The reduction of the error band on M_H (the, so called, blue-band in Fig. 3) is predicated on being able to incorporate further theoretical refinements in the existing radiative correction programs. Ideally, one really wants the full $O(\alpha^2)$ corrections to M_W and $\sin^2\theta_W^{\text{eff}}$, since the dominant $O(\alpha^2 m_t^4)$ corrections are quite non-negligible. For instance, these corrections give a contribution to the W-mass of $\delta M_W \sim 15$ MeV. In this conference, P. Gambino [8] and G. Weiglein [42] reported on some partial results for the $O(\alpha^2)$ corrections. Gambino discussed the $O(\alpha^2 m_t^2)$ subleading corrections, which give mass shifts $\delta M_W \sim 10$ MeV. These corrections have been incorporated in the fitting programs. Weiglein discussed the full **fermionic** $O(\alpha^2)$ corrections. Because these corrections are not by themselves under control, what Weiglein computes is really the shift in M_W as one changes M_H away from some reference value. Where comparable, the computations of Weiglein and Gambino are in very good agreement with each other, with "theoretical" errors at most of $O(\delta M_W \sim 1$ MeV$)$.

5   Future Tests

In Barcelona, a trio of talks [43,44,45] were presented detailing how future machines can contribute to precision electroweak measurements. Although LHC, or the proposed linear e^+e^- colliders and muon colliders are primarily discovery machines, it turns out that asking questions of how these machines can contribute to future precision measurements provides an important and useful challenge which helps refine one's thinking.

For each machine, the questions one asks are in general different. For example, for the LHC, [43] to be able to do precision measurements, it will be necessary to calibrate the leptonic energy to 2×10^{-4}; measure the jet energy to $O(1\%)$; and measure the luminosity at the 5% level. If one can achieve this, then using a large statistical sample one can hope to reduce the errors in M_W, m_t, and M_H to:

$$\delta M_W \leq 15 \text{ MeV} ; \quad \delta m_t \leq 2 \text{ GeV} \tag{35}$$

and, for $M_H < 500$ GeV,

$$\delta M_H / M_H \sim 10^{-3} \ . \qquad (36)$$

It was clear in Barcelona that each of the three future accelerators discussed have complementary physics reaches. For instance, the $\mu^+\mu^-$ collider is an excellent Higgs factory which, for $M_H \sim 100$ GeV, has a chance to determine the Higgs mass and width to very great accuracy [$\delta M_H \sim 100$ KeV; $\delta\Gamma_H \sim 500$ KeV]. Furthermore, as Blondel [45] explained, because the beamstrahlung is reduced by a factor of $(m_e/m_\mu)^4$ with respect to an e^+e^- collider, one can study the threshold production properties of top much better at a μ-collider than at a linear e^+e^- machine. Blondel estimated that one could achieve an error on the top mass of $\delta m_t = 100$ MeV in a μ-collider. Furthermore, if one ran the collider as a Z-factory, it may be possible to actually tune the muon spin so that it flips at each turn! However, there are enormous technical problems to overcome to make a muon collider a reality. One needs to have intense sources of muons which necessitate initial proton fluxes almost a thousand times what has been achieved to date. Furthermore, there is no real solution still on how to effectively reduce the muon phase space through cooling, or how to shield the detectors from the debris arising from muon decays. So, the potential for physics of such a machine may never be realized.

In this respect, as Miller [44] discussed, e^+e^- colliders are much closer to a technical solution, both for the case of the X-band machine proposed by SLAC and KEK and for the superconducting rf project (Tesla) championed by DESY. Although beamstrahlung will be a significant headache, these machines can be wonderful tools for studying relatively light Higgs bosons and possible supersymmetric partners of existing particles. For example, for an integrated luminosity of $\int L dt \sim 50$ fb^{-1} at $\sqrt{s} = 500$ GeV, the production of a 100 GeV Higgs boson will be rather copious, with approximately 3000 $e^+e^- \to ZH$ events and 6000 $e^+e^- \to \nu\bar{\nu}H$ events. With this kind of data sample, one can hope to study the relative branching ratios of Higgs decay into fermion-antifermion pairs (mostly $b\bar{b}$, but also significant $\tau\bar{\tau}$ pairs) with considerable accuracy. Furthermore, the availability of polarized electron beams should help to disentangle the coupling structure of light supersymmetric particles, through the study of the characteristic angular correlation structure of their decay by-products.

The situation is perhaps even more favorable, in some respects, with the LHC. As Gianotti explained,[43] perhaps the most important fact is that the LHC is under construction and should actually begin taking data around 2005!

Furthermore, the LHC, because of its large CM energy, can look for supersymmetry over a wide range of masses—roughly $m_{\tilde{q}}, m_{\tilde{g}} \leq 2$ TeV. In addition, the LHC has also the ability to do rather precise mesurements of the masses and couplings of supersymmetic particles, if they exist in this mass range. In this respect, as was emphasized in RADCOR 98 by a number of speakers, it is important to continue to refine the strategies of how to look for possible signals, as these in general arise from a sequence of decays.

Another important lesson for the LHC is to carefully try to incorporate the result of radiative effects, as these can substantially change expectations. This was demonstrated in Barcelona in a number of instances. For example, Djouadi[46] showed how a light stop can depress the cross section times branching ratio for the production and decay of a light SUSY Higgs into two photons. Radiative effects can also change substantially the effective $\bar{t}bH^+$ coupling, thus affecting the expectations both for top decays, if the charged Higgs is light,[47] or H^+-decays, if the charged Higgs is heavy.[48] Spira[49] discussed NLO QCD corrections for the production of squarks, gluinos and charginos, and showed that also here these can be rather substantial, leading to typical K-factors of 1.2-1.5. Clearly one will be able to much better judge the importance of these effects when, and if, supersymmetric particles are found. However, one should be aware that naive lowest order calculations may well not suffice to properly extract the underlying supersymmetric parameters, once a signal of supersymmetry is detected.

However, as Haber[50] and Pokorski[51] emphasized in Barcelona, it may not be necessary to wait for the LHC to see new physics! The most solid prediction of having supersymmetry at the electroweak scale is that there should exist in the spectrum a light Higgs boson. The light Higgs, h, is the lightest of the two neutral 0^+ bosons present in all supersymmetric theories. Neglecting radiative effects, its mass is bounded by that of the Z: $m_h < M_Z$. Radiative effects, however, can give large mass shifts so that the above bound is only indicative. Nevertheless, as Weiglein[42] and Haber[50] discussed, these radiative mass shifts are controlable. Indeed, one has a 2-loop RG improved result, accurate to $O(\alpha\alpha_s)$, which gives this shift to a few percent accuracy. This shift is proportional to the running top mass and depends logarithmically on the underlying supersymmetric parameters

$$\Delta m_h^2 \sim G_F m_t^4(m_t) \; \ln M_{\mathrm{SUSY}}^2/m_t^2 \; . \tag{37}$$

The resulting light Higgs mass has a maximum for large $\tan\beta$ and when the mass of the 0^- neutral Higgs m_A is also large. Typically, m_h is bounded by $m_h \leq 130$ GeV, with the bound weakening as $\tan\beta$ decreases. For example,

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as de Boer [11] discussed, $m_h \leq 105$ GeV for $\tan\beta = 1.6$.

The above results have important experimental implications. Already LEP 200 has good limits on m_h and m_A, with the combined data of all four LEP experiments at $\sqrt{s} = 183$ GeV giving the bounds (for $\tan\beta > 0.8$) [52]

$$m_h > 77 \text{ GeV} \; ; \;\; m_A > 78 \text{ GeV} \; . \tag{38}$$

As the LEP 200 energy is moved to $\sqrt{s} = 200$ GeV, these limits can be pushed up probably another 10 to 15 GeV, depending on what the total integrated luminosity will be. Hence, it could well be that a light Higgs—of the type predicted by supersymmetry—may be within the reach of LEP 200. The Tevatron too, if it can achieve higher luminosity after its first run with the Main Injector, has a shot at discovering this physics. For instance, if one can achieve at the Tevatron $\int \mathcal{L} \, dt \sim (20 - 25) \text{ fb}^{-1}$, one can probe for the existence of a light Higgs up to $m_h \leq 120$ GeV, [52] well within the expectation of supersymmetric models. Obviously, this is an important goal to try to pursue!

Acknowledgements

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